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Power plant component design using creep and fatigue damage analysis

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Abstract: Structural analysis and design of power plant components requires us to take into account inelastic deformation and material damage processes under constant and variable loading and temperature conditions. The aim of this presentation is to introduce the constitutive models of creep and damage for advanced heat resistant steels. An emphasis is placed on the description of ductile-brittle transition of the damage mode depending on the applied stress level and the duration of the creep process. The model is applied to the lifetime prediction of a real power plant component. For this purpose a user-defined material subroutine is developed inside a general finite element code. The results of computations illustrate basic features of the stress redistribution and the damage evolution during isothermal loading cycle. Based on the obtained stress, strain and damage fields, we discuss the extensions of the proposed method to non-isothermal variable loading.

Keywords: Creep, Fatigue, Damage, Power Plant Component.

1 Introduction

Many important components of steam turbines are subjected to high temperature environments and complex loading conditions over a long time of operation. Design procedures and residual life assessments for pipe systems, rotors, turbine blades, turbine and valve casings etc. require us to take into account creep and damage processes. The aim of "creep modeling for structural analysis" is the development of methods to predict time-dependent changes of stress and strain states in engineering structures up to the critical stage of creep rupture [1,2]. Structural analysis under creep conditions requires a reliable constitutive model which reflects time-dependent creep deformations and processes accompanying creep, like hardening/recovery and damage. An important feature of the creep constitutive modeling is the ability to extrapolate the laboratory creep data usually obtained under increased stress and temperature to the in-service loading conditions. Conventional creep modeling is based on the power law response functions of stress. An example is the *Kachanov-Rabotnov-Leckie-Hayhurst* constitutive model (see [1,2]). In this paper we address the creep analysis of heat resistant steels for a wide stress range including low and moderate stress values. Based on the available experimental data the creep constitutive equation and the damage evolution equation are discussed. The continuous response functions are proposed which allow us to fit creep behavior to a wide range of stresses and temperatures. The proposed damage evolution equation takes into account the change of the damage mode (brittle, ductile or mixed) depending on the stress level as well as on the kind of stress state. The constitutive model is incorporated into the *ABAQUS* finite element code by means of a user-defined subroutine. To verify the constitutive assumptions an example for a real power plant component is presented. The results of creep analysis under isothermal conditions illustrate that the proposed approach is able to reflect basic features of stress redistribution in the structural component. Furthermore, the location of critical damage zones is predicted adequately. Based on these results a combined approach to consider the fatigue damage accumulation due to the loading transients is discussed.

2 Constitutive models of creep and damage

Within the phenomenological approach to creep modeling one usually starts with the constitutive equation for the minimum (secondary) creep rate. To characterize the hardening/recovery and damage processes this equation is generalized by introduction of the internal state variables and appropriate evolution equations. In what follows we limit ourselves to the description of secondary and tertiary creep stages only. To this end the creep constitutive equation and the damage evolution equation will be discussed. Regarding the hardening variables and hardening rules one may consult comprehensive reviews, for example [3,4]. The conventional phenomenological model characterizes the secondary creep rate with the power law stress function and includes the effect of tertiary creep by means of the single scalar-valued damage parameter [2,5]. It can be presented as follows:

$$\dot{\boldsymbol{\varepsilon}}^{cr} = \frac{3}{2} a \left(\frac{\sigma_{vM}}{1-\omega} \right)^n \frac{\mathbf{s}}{\sigma_{vM}}, \qquad \dot{\omega} = b \frac{[\alpha \sigma_T + \beta \sigma_{m+} + (1-\alpha-\beta)\sigma_{vM}]^k}{(1-\omega)^l}, \tag{1}$$

$$\sigma_{vM} = \sqrt{\frac{3}{2}\mathbf{s}\cdot\cdot\mathbf{s}}, \quad \sigma_{m+} = \frac{1}{6}(\mathrm{tr}\boldsymbol{\sigma} + |\,\mathrm{tr}\boldsymbol{\sigma}\,|), \quad \mathbf{s} = \boldsymbol{\sigma} - \frac{1}{3}\mathrm{tr}\boldsymbol{\sigma}\,\mathbf{I}, \quad \sigma_T = \frac{1}{2}(\sigma_I + |\sigma_I|).$$

In this notation $\dot{\boldsymbol{\varepsilon}}^{cr}$ is the creep strain rate tensor, $\boldsymbol{\sigma}$ is the stress tensor, $\mathbf{s}$ is the stress deviator, σ_{vM} is the *von Mises* stress, σ_T is the maximum tensile stress, σ_I is the first principal stress, σ_{m+} is the positive mean stress, $\mathbf{I}$ is the second rank unit tensor and ω is the damage parameter. The weighting factors α and β characterize the influence of the principal damage mechanisms (σ_T-controlled, σ_{m+}-controlled or σ_{vM}-controlled). a, b, n, k and l are material constants, which are determined from creep tests at a constant temperature. The equations (1) can be applied only to the case of constant temperature. To generalize them to the non-isothermal conditions the material constants a and b should be replaced by the functions of temperature. Assuming the *Arrhenius* type temperature dependence the following relations can be utilized

$$a(T) = a_0 \exp\left(-\frac{Q_a}{RT} \right), \quad b(T) = b_0 \exp\left(-\frac{Q_b}{RT} \right), \tag{2}$$

where Q_a and Q_b are the activation energies of creep and damage processes, respectively, R the universal gas constant, T absolute temperature and a_0, b_0 creep constants. To identify the material constants in equations (1) experimental data of uni-axial creep up to rupture are required. The identification procedure is presented in [6], for example. Model (1) has been widely used to characterize creep and long-term strength of materials and structures. Examples of material constants as well as structural mechanics applications can be found in [2,6,7], among others. However the model (1) guarantees the correct prediction of the creep and damage rates only for a certain stress range. To discuss the range of validity let us consider the uni-axial stress state with the tensile stress σ. In this case equations (1) provide the following relations

$$\dot{\varepsilon}^{cr}_{min} = a\sigma^n, \quad t_* = \frac{1}{B\sigma^k}, \quad \varepsilon^{cr}_* = C\sigma^{n-k}, \qquad B \equiv (l+1)b, \quad C \equiv \frac{a}{b(l+1-n)}, \tag{3}$$

where $\dot{\varepsilon}^{cr}_{\min}$ is the minimum creep rate, t_* is the time to fracture and ε^{cr}_* the creep strain before fracture (creep ductility). The plots of equations (3) in a double logarithmic scale represent straight lines. Figure 1a shows a typical dependence of the minimum creep rate on the applied stress, usually observed for advanced heat-resistant steels. Here the ranges of "low", "moderate" and "high" stress values can be distinguished. Within the range $0 \le \sigma \le \sigma_0$, where σ_0 is the transition stress, the creep rate is a nearly linear function of the stress. The "moderate" stress range is characterized by the power law creep. The value of the creep exponent lies in the range between 4 and 12 depending on the material, type of alloying and processing conditions. Within the region of "high" stresses the power law breakdown is usually observed. The experimental data for 9%Cr-steel presented in [8] show that within the moderate stress range the creep exponent takes the value 12. Figure 1b illustrates a typical long term strength curve, i.e. the dependence of the time to creep rupture on the applied stress. The available data for the range of "low" stresses suggests that the damage evolution is primarily determined by the nucleation and growth of inter-granular cavities and micro-cracks. We assume that the damage rate is controlled by the maximum tensile stress σ_T. For moderate stresses the damage evolution has the mixed (brittle-ductile) mode. The damage criteria proposed for this stress range include both the maximum tensile stress and the *von Mises* equivalent stress. An example is the equivalent stress in the damage evolution equation (1). With increase of the stress value the creep damage becomes primarily ductile and leads to the necking of the uni-axial specimen. The additional damage mechanisms for the low and moderate stress ranges are the microstructure degradation processes, e.g. the sub-grain coarsening and coarsening of carbide precipitates. The experimental data for long term strength of 9%Cr-steel under different temperature values are presented in [9], among others. Creep and long-term strength behavior for the "moderate" stress range (shaded zones in Figure 1) can be described by equations (1) with sufficient accuracy. One way to extend the model to the wide stress range is the introduction of several damage variables associated with different micro-structural changes and corresponding evolution equations, for example [10]. However, such an approach requires the knowledge of microstructure degradation kinetics and the identification of many additional material constants.

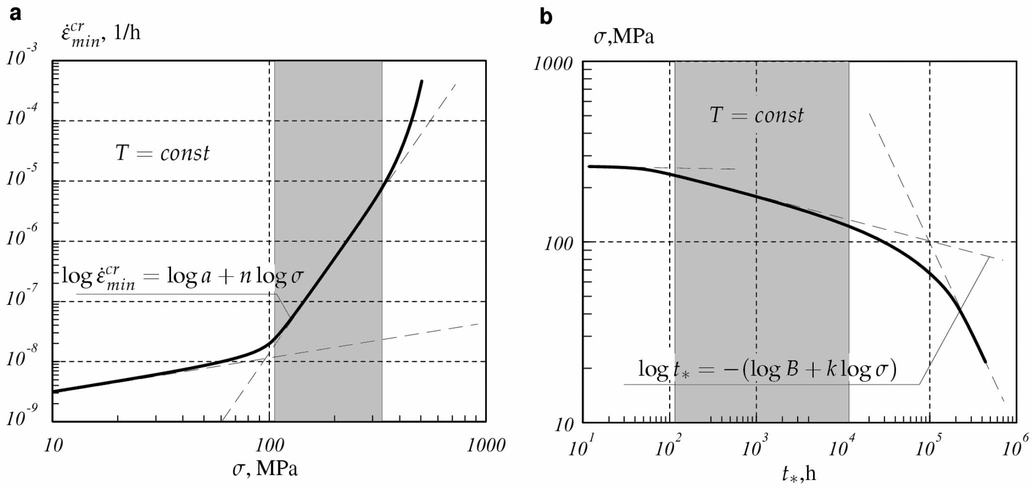

Figure 1. Sketch of creep behavior for heat resistant steels: a) minimum creep rate vs. stress, b) stress vs. time to rupture

Here we limit our attention to the ranges of "low" and "moderate" stresses only and propose to extend the material model (1) as follows

$$\dot{\varepsilon}^{cr} = \frac{3}{2} a \left(\sigma_{vM} + \left(\frac{\sigma_{vM}}{\sigma_0 (1-\omega)} \right)^n \right) \frac{\mathbf{s}}{\sigma_{vM}}, \quad \dot{\omega} = \frac{b}{(1-\omega)^l} \left(\left(\frac{\sigma_T}{\sigma_0} \right)^k + \frac{l+1}{n+1} \left(\frac{\sigma_{vM}}{\sigma_0} \right)^n \frac{1}{(1-\omega)^{n-l}} \right), \tag{4}$$

where the temperature dependent material constants a, b and σ_0 as well as the exponents n, l and k were identified from the experimental data for a typical heat-resistant 10%Cr-steel presented in [11]. The creep constitutive equation in (4) allows us to fit the transition from the linear to the power law creep. The damage evolution equation in (4) includes the transition from the pure brittle (σ_T-controlled) to the pure ductile (σ_{vM}-controlled) damage mode. The material constants, the creep curves as well as the isochronous rupture loci according to model (4) will be discussed in a forthcoming paper.

3 Structural analysis for constant loading and isothermal conditions

Structural analysis under creep conditions usually requires: a suitable structural mechanics model based on assumptions about kinematics of deformations, types of internal forces (moments) and related balance equations; a reliable constitutive model which is able to reflect time-dependent creep deformations and processes accompanying creep like hardening/recovery and damage; a mathematical model of the structural behavior (initial-boundary value problem); numerical procedures to solve non-linear initial-boundary value problems and the verification of applied models. The first two steps are common within continuum and engineering mechanics. Here mathematical models of three-dimensional solids, beams, rods, plates and shells are preferred. In creep mechanics they are applied together with constitutive and evolution equations describing the creep-damage behavior. In recent years the finite element method has become the widely accepted numerical tool for structural analysis. In its application to the creep analysis one should take into account that a general purpose constitutive equation which allows to reflect the whole set of creep and damage processes in structural materials over a wide range of loading and temperature conditions is not available at present. Therefore, a specific constitutive model with selected internal state variables, special types of stress and temperature functions as well as material constants identified from available experimental data can be incorporated into the commercial finite element code by user-defined material subroutines. An important question concerns reliability of the applied models, numerical methods and obtained results. The reliability assessment may require: verification of developed finite element subroutines; verification of applied numerical methods and verification of constitutive and structural mechanics models. Several benchmark problems for simplified structures including beams, transversely loaded thin plates and thick-walled pipes are presented in [2,6]. Special semi-analytical techniques have been applied to find a reference solution without the finite element meshing. Finite element solutions for the same problems allow us to verify the user-defined creep-damage subroutines over a wide range of finite element types including beam, shell and solid elements. Furthermore, the problems of the suitable finite element mesh density, the time step size and the time step control have been analyzed. To discuss the applicability of the developed techniques to real engineering problems, results of finite element analysis for real power plant components must be compared with data collected from engineering practice. In [2] an example for a spatial steam pipeline is discussed. In [6] creep behavior of a valve casing is analyzed. In these examples the *Kachanov-Rabotnov-Leckie-Hayhurst* model (1) has been utilized.

Figure 2 illustrates the results of finite element analysis (FEA) for an idealized casing geometry of a steam turbine control-stop valve subjected to constant internal pressure and uniform heating. Such a component has to control and/or to stop the steam flow into a steam turbine. The computations are based on model (4). Due to the confidentiality of geometry and of material parameters, the results for the relevant stress and load time range in the valve casing were artificially changed. Accordingly the results should be considered just in a qualitative manner. As a consequence of the stress redistribution the maximum principal stress relaxes and reaches its maximum value at design lifetime t_{DL} as shown in Figure 2a. For this stress condition the damage evolution is primarily controlled by the maximum tensile stress and is predominant in the outer surface of the casing as shown in Figure 2b.

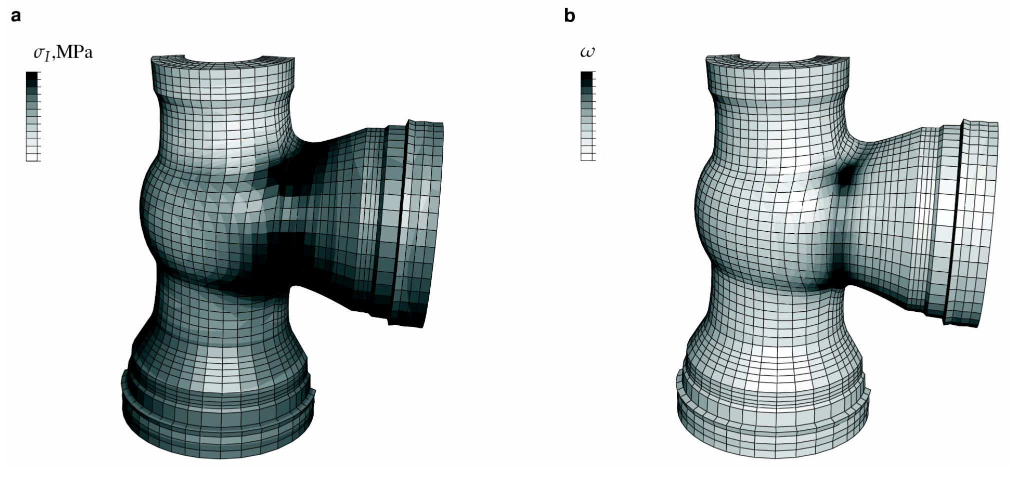

Figure 2. Results of the FEA for an idealized valve casing, black indicates a high level: a) distribution of the first principal stress at t_{DL}, b) distribution of the damage parameter at t_{DL}

Therefore, the brittle damage mode associated with the formation of micro-voids and micro-cracks is expected in this region. Let us note, that such a conclusion can not be made if we apply the creep-damage model (1). In fact, the kind of the damage mode in (1) is fixed by the constant weighting factors a and b and does not depend on the stress level.

4 Consideration of fatigue damage

Modern power plant components must withstand severe cyclic mechanical and thermal loads throughout the whole life cycle. The principal mechanism of the non-isothermal mechanical fatigue damage is the initiation and growth of micro-cracks. The critical cyclic loads (deformations) leading to the fatigue fracture are quite different if compared to the critical load values in the static case. In what follows we limit ourselves to the case of the low cycle fatigue (LCF), that is to say, to the case that the failure could occur in less than 10^4 cycles. To estimate the lifetime of the component and to predict the location of the critical failure zones creep-fatigue accumulation rules are required. Unified constitutive models were developed which are able to reflect the effects of creep-plasticity as well as static-cyclic damage accumulation. A review of such models is presented for example in [12]. Let us note, that the identification of material constants in a unified model requires experimental data for inelastic behavior under variable loading with holding time, and under loading magnitudes which could occur in a real component. Such data, particularly for the multi-axial loading conditions, are rarely available. Furthermore, the computational procedure for the whole structure under variable loading and non-uniform heating is quite expensive. Based on the results of the creep-damage analysis let us discuss the simplified procedure, which consists in the following steps: perform FEA of creep and find the location of critical zones of creep damage as discussed in Section 3; calculate stress, strain and temperature fields for the most dominant operating cycle based on the transient analysis; estimate the strain range using a shakedown approach based on the *Neuber's* rule [13]; calculate the allowable number of cycles using the experimental data for strain vs. number of cycles; estimate the total damage according to the results of the creep and fatigue damage analysis and the linear damage accumulation rule. The approaches to the shakedown and LCF analyses are based on the stabilized cyclic stress-strain curve and the strain-cycle curve of the considered material. The stress-strain curve can be approximated by the *Ramberg-Osgood* type law [11,14] as follows

$$\varepsilon_a = -\frac{\nu}{E}\,\mathrm{tr}\,\sigma_a + \frac{1+\nu}{E}\sigma_a + \frac{3}{2}\left(\frac{\sigma_{vM\,a}}{K'}\right)^{\frac{1}{n'}} \frac{\mathbf{s}_a}{\sigma_{vM\,a}}, \tag{5}$$

where ε_a and σ_a are the amplitudes of the strain and stress tensors, respectively. E is the *Young's* modulus, ν is the *Poisson's* ratio, K' is the yield strength and n' is the hardening exponent. The strain-cycle curve can be approximated by the *Manson-Coffin* [15,16] equation

$$\varepsilon_{vM\,a} = \alpha_1 N_A^{\beta_1} + \alpha_2 N_A^{\beta_2}, \tag{6}$$

where α_1, α_2, β_1 and β_2 are material constants and N_A is the number of cycles to failure. To take into account the influence of the mean stress we apply the following fatigue parameter

$$P = \sqrt{\kappa(\sigma_m + \sigma_a)\cdot\cdot\varepsilon_a}, \tag{7}$$

where κ is the material constant. For the uni-axial stress state and with $\kappa = E$ the *Smith-Watson-Topper* parameter [17,18] follows from (7). This parameter is valid for a lot of materials and is commonly applied in industry and science. The accumulated fatigue damage over the n loading cycles D_f and the total accumulated damage D are estimated correspondingly with a generalized approach [19,20] by

$$D_f = \sum_{i=1}^{n} \frac{n_i}{N_{A_i}}, \quad D = \omega + D_f, \tag{8}$$

where D does not exceed a theoretical value of 1. The calculation method was applied for estimation of fatigue damage occuring during start-up and shut down in a steam turbine control-stop valve casing with an idealized geometry, as in Figure 2. The experimental material data for the 10%Cr-steel were used for determination of material constants in equations (5) and (6). From equation (6) and a regression method (e.g. *Newton's* method) an allowable number of cycles till crack initiation was obtained. The calculated fatigue damage value D_f and the creep damage parameter ω make up the total accumulated damage D, which does not exceed the allowable value of the analyzed valve casing at the design lifetime t_{DL}.

5 Conclusions and recommendations

In this paper the isotropic creep-damage model was applied to predict the creep and fatigue damage in a steam turbine component. The proposed method is based on the detailed FEA of creep and damage processes in a structural component. The constitutive model of creep includes the ductile-brittle transition of the damage mode depending on the stress level and the type of stress state. The proposed model is able to reflect the basic features of stress redistribution in the structural component.

The example of steam turbine control-stop valve casing illustrates that the developed method is capable of reproducing basic features of creep in engineering structures including time-dependent changes, stress redistributions and formation of critical zones of creep failure. The results of FEA were used for the subsequent LCF fatigue analysis. To refine the creep-fatigue life estimations, further studies on the stress state effects are required. These results should be investigated further in order to find out how to come closer to reality. Such clarification could give important input for future improvements in high temperature component design. In this context, firstly the parameter identification should be optimized for the relevant loading, whereby also multi-axial experiments should be used. Moreover, it is very important to compare and review the numerical damage predictions with respect to experimental findings of uni-axial and multi-axial load cases. Furthermore, the method should be qualified for different materials and thermal cycles. The good correlation between the predicted and the measured lifetime for the uni-axial tests is encouraging.

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